

AutoSolar Thermal Electric Conversion (ASTEC) Solar Power System:

CROSS REFERENCE TO RELATED APPLICATION

5 [0001] This application claims benefit under 37 C.F.R. §119 (e) of US provisional
6 Application Ser. No. 60/443,692 filed January 28, 2003, the entire contents of
7 which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

10 [0002] Billions of dollars have been spent in solar energy R&D, and tens of
11 thousands of solar energy devices and systems have been built, sold, and installed
12 across the US. All have been inherently so expensive that they have been cost-
13 supported by tax relief schemes or rebates, and all are utterly unable to compete
14 economically with conventional power plants and heat-power systems. The result
15 of these billions of dollars of R&D is that these solar power systems can NOT
16 provide low-cost power to the consumers of this or any other Nation.

[0003] This failure of solar power R&D to yield useful systems is precisely because it was conducted as R&D, not as construction of systems from available low-cost heat-power machinery. The excessive cost of all past solar power systems is a direct result of this struggle to develop and employ equipment and systems of advanced high technical performance.

SUMMARY OF THE INVENTION

[0004] In accordance with principles of embodiments of the invention, solar power can be made inexpensively, but not with high-tech R&D products, but rather by use of proven, reliable heat-power equipment and devices which are mass-manufactured in the tens of millions by the US automotive, air conditioning and refrigeration industries. This approach abandons the scientist's desire for high efficiency and advanced technical performance, in favor of the investment

1 community's criterion of product low-cost and high rate—of-return on
2 investment.

3 [0005] Thus, in accordance with embodiments of the invention, the path taken is
4 to seek systems which offer high economic performance at low cost. This means
5 simple systems, and equipment of modest performance, derived from a large
6 volume manufactured industrial base. The major hardware portions (flat plate
7 collectors, heater-vaporizer heat exchanger, pumps, valves etc.) of the AutoSolar
8 Thermal Electric Conversion (ASTEC) solar power system described herein
9 requires no R&D; rather already existing technologies and equipment from the
10 world of heavy manufacturing are utilized.

11 [0006] The ASTEC system utilized, in part, the hundred year old Rankine cycle.
12 Rankine cycles use a working fluid, vaporized in a heater, to drive an expansion
13 engine producing shaft power, then condensed in a condenser heat exchanger, and
14 pumped back at higher pressure back to the heater. The shaft power turns a
15 generator for electrical power output. The heater is supplied with thermal energy
16 from a solar energy collector system, and waste heat is removed from the
17 condenser by rejection to ambient air.

18 [0007] The most reliable and lowest cost expansion engine in the world is the
19 automotive engine, manufactured in the tens of millions each year. Because of
20 this, auto engines have the least costly swept volume of any heat-power engine on
21 the planet. Heater and condenser heat exchangers are also least costly from the
22 auto industry. Both functions for the low-cost ASTEC system can be served by
23 the multi-million manufactured auto engine radiators, which are the cheapest heat
24 exchangers (per unit heat transferred) in the world. This leaves only the solar
25 collector system.

26 [0008] Collectors are fabricated at low cost from the mass-manufactured back
27 plates which reject heat in (older) conventional refrigeration systems. These form
28 the main collection elements in the complete collector unit, which uses double
29 pane thin-glass covers, modest back insulation and mounting in a low-cost wood

1 frame box. The fluid to be used in the collector plates may be either water or a
2 standard heat transfer oil (e.g. Dowtherm A). Thermal energy storage , to allow
3 system power generation during dark time (night), can be provided at very low
4 cost by use of the cooling fluid (e.g. water) stored in a simple insulated tank,
5 which supplies heated fluid to the Rankine cycle fluid heater radiators.

6 [0009] The optimum fluid for the Rankine expansion cycle circuit through the
7 expansion engine is the modern replacement for Freon refrigerant (e.g. R-123 vs
8 Freon-11, etc). If water is used in the collector circuit, the entire cycle operates
9 only between the upper temperature limit of about 210 F in the heater, and a
10 lowest temperature of 60 F (winter) to 100 F (summer) in the condenser heat
11 exchanger. In this temperature range, and with the appropriate refrigerant working
12 fluids, the system heater pressure will not exceed 200-240 psia at engine inlet, and
13 the lower pressure at engine exhaust can be kept below 22-25 psia. Because of
14 these low temperatures and pressures, virtually no wear will occur on the
15 equipment, whose lifetime is thus measured in decades, as for conventional
16 refrigeration systems.

17 [00010] While the overall efficiency of utilization of solar energy is also
18 low because of these low temperatures, the extremely low cost of the equipment,
19 and of the assembled system, leads to low-cost for the output power. The cost of
20 this solar thermal conversion power plant is determined by the costs of its
21 equipment and systems components, and by the cost of their assembly and field
22 installation. The system/equipment costs arise principally from its two main
23 subsystems. These are:

- 24 1. The thermal conversion system, including all heat
25 exchange elements.
- 26 2. The solar collector system that acquires energy
27 during the day and the thermal energy storage system that
28 provides energy during night time.

29

1 [00011] Additional costs will be accrued for electrical power generation,
2 controls, switching, pumps, valves, piping, system housing and other
3 miscellaneous items. Thus costs must be accounted for::

4 3. The main electrical generator system, controls,
5 switchgear, power line interfacing.

6 4. The flow pumps, piping and controls

7 5. A protective building for engine/generator and
8 waste heat radiator subsystems.

9 [00012] Of these, the dominant cost is that of the collector system. This
10 results directly from the fact that the solar insolation (power flux and fluence)
11 falling on the Earth's surface is diffuse and relatively weak, being about 1.34
12 kWth/m² on the top of the atmosphere at the subsolar point.

13

14 **BRIEF DESCRIPTION OF THE DRAWINGS;**

15 [00013] Fig. 1 shows an overall block diagram of the Rankine cycle
16 utilized in embodiments of the invention.

17 [00014] Fig. 2 shows a the (measured) performance of an ASTEC system
18 collector panel operating without any cooling-working fluid.

19 [00015] Figs. 3-8 show block diagrams of the elements of the ASTEC
20 system with the working fluid flow path shown during various times as depicted
21 in Fig. 2.

22 [00016] Fig. 9 shows an arrangement of one embodiment of a group of
23 panels.

24 [00017] Fig. 10-12 show working fluid flows through various arrangements
25 of solar panels.

1 [00018] Figs. 13 and 14 show cross sectional views of solar panels
2 according to embodiments of the invention.

3 [00019] Fig. 15 shows an exploded view of a solar panel according to an
4 embodiment of the invention.

5 [00020] Fig. 16 shows an L shaped support bracket for a set of solar panels
6 for supporting same at a fixed optimal inclination angle.

7 **DETAIL DESCRIPTION OF PREFERRED EMBODIMENTS**

8 **Solar Insolation, Absorption and Capture Efficiency**

9 [00021] Data have been taken over many years for solar insolation in the
10 US. It has been found that areas with the highest solar flux/fluence are in the
11 Southwest, including Southern California, Arizona, New Mexico and parts of
12 Texas. Here, measurements show that the total solar energy fluence (F_0) incident
13 on a surface perpendicular (normal) to the sun during the daylight hours (requires
14 turning the incident surface to make this measurement) varies from about $F_0=10$
15 kWthhrs/m² in the summer (June) months to $F_0 = 5$ kWthhrs/m² in the winter
16 (December). For design purposes for the ASTEC system solar power system, the
17 average normal summer insolation has been taken as $F_{os} = 9.6$ kWthhr/m² and
18 that in the winter as $F_{ow} = 4.8$ kWthhr/m².

19 [00022] Realistic economic considerations make tracking collectors
20 impractical, as the increased collection achieved is generally not worth the
21 considerable cost of the tracking and mounting systems, flexible piping, etc. The
22 ASTEC system of interest here is thus limited to use of flat plate collectors that do
23 not turn to follow the sun.. However, it is easy, cheap and practical to mount these
24 fixed collectors so as to face the sun at high noon, and thus to capture the
25 maximum amount of sunshine during the day without moving. For such
26 collectors, the total solar energy that can be collected will then vary significantly
27 from sunrise to sunset. At these two extremes, no sunshine will be collected. As
28 the sun is higher above the horizon, it “sees” more and more of the collector

1 surface, which is then heated higher with increasing sun angle. However, the
2 effective absorption of the collector surface also varies with sun angle, being less
3 at small angles and more at normal incidence. The absorption coefficient varies
4 about as the sine of the sun angle. And the solar flux incident on a fixed normal-
5 at-noon collector also varies as the sine of the sun angle. The result of these two
6 variations is that the collected solar flux varies as the square of the sine of the sun
7 angle. The solar flux can thus be written as a function of the hour of the day (t, in
8 24 hour clock system), for the angle in degrees, as

9 $f_{sol} = [F_o] [\sin^2(15t)] \text{ kWth/m}^2 \text{ for } 6:00\text{am} < t < 6:00\text{pm}$

10 [00023] Where F_o is the total fluence for any given month of the year,
11 varying from the summer to winter values as discussed above. When this formula
12 is examined over any given day, it is immediately seen that such a collector
13 system will be practically useful only over about 3/4 of the daylight hours, around
14 noontime. The time spent with the sun below 30 degrees of the horizon does not
15 contribute significantly to the total energy collected.

16 [00024] Although quite conservative, this formula has been used in the
17 design of the ASTEC system collector system here. This means that the actual
18 performance of the system will be somewhat better than the design values cited
19 later for the complete system.

20 Rankine Cycles, Engine Expanders and Performance

21 [00025] The 125-year-old Rankine cycle is a very simple one. Its basic
22 elements are shown in the schematic block diagram of Fig. 1. Here we see its
23 principal elements as a pump, heater/vaporizer, expander (engine) and
24 cooler/condenser, all acting on and from the working fluid that is flowing through
25 the system. Cold, dense fluid at point (1) in the cycle is pumped to high pressure
26 by point (2), and then vaporized in the heater/vaporizer between points (2) and
27 (3), to arrive at point (3) as a high pressure gas. This gas is then expanded through

1 the engine to point (4) making shaft power as it goes, and is then condensed in the
 2 cooler/condenser to return as dense liquid to point (1).

3 [00026] The efficiency of the Rankine cycle is just the ratio of the shaft
 4 power out to the total power into the fluid. The maximum possible power output
 5 from such a heat/power flow cycle is measured by the enthalpy (h) usefully
 6 extracted from the fluid in the cycle. Enthalpy is just the energy content per unit
 7 mass of fluid at any point in the system. The maximum efficiency of conversion is
 8 then just the ratio of the extracted enthalpy change in the expander, minus the
 9 enthalpy addition in the pump, divided by the total enthalpy change in the fluid
 10 from its highest value (at 3) to its low point (at 1). This is called the

11 [00027] Carnot cycle efficiency and is found to be simply the ratio of the
 12 maximum to minimum temperature difference to the maximum temperature in the
 13 flow system. This is

$$14 \quad \text{Efficiency} = \frac{\text{Shaft power out}}{\text{Total power in}} = \frac{(h_3-h_4) - (h_2-h_1)}{(h_3-h_1)} = 1 - \left(\frac{T_{\text{cooler}}}{T_{\text{heater}}} \right)$$

15

16

17

18 [00028] The *actual* efficiency of this cycle will always be less than this
 19 expression, because of temperature differences in the heat exchange process in the
 20 heater and cooler, non isentropic pumping and expansion processes, losses at fluid
 21 intake and exhaust valving to and from the engine, and non-isothermal heat
 22 addition and extraction in the heat exchangers. All of these together generally
 23 reduce the efficiency below the Carnot cycle value, above, to a level of 0.7-0.8 of
 24 Carnot efficiency.

25 [00029] In accordance with some embodiments of the invention, the
 26 ASTEC power system is predicated on the use of fluid cycle temperatures so low
 27 that they can (a) be supplied by fixed flat plate collectors of very low cost (no
 28 high-tech), and (b) be used with refrigerant fluids in low temperature expansion
 29 cycle

$$\text{Efficiency} = \frac{\text{Shaft power out}}{\text{Total power in}} = \frac{(h_3-h_4) - (h_2-h_1)}{(h_3-h_1)} = 1 - \left(\frac{T_{\text{cooler}}}{T_{\text{heater}}} \right)$$

1 equipment with extremely long life and reliable performance, and of low-cost
2 manufacture (no high pressures, or high temperatures involved). Thus, the range
3 of upper fluid temperatures must lie from 300 degrees F (for use of oil as heat
4 transfer fluid in the collector system) to 200 degrees F (for use of water as the
5 fluid in the collector system). The low heat rejection temperature of the power
6 system will range from 60 degrees F (in winter) to 100 degrees F (in summer), for
7 the lowest cost waste heat rejection to ambient air, using mass-produced auto
8 radiators.

9 [00030] With these temperatures the Carnot efficiency will vary from 0.32-
10 0.26 for the oil coolant, to 0.21-0.15 for the water coolant, over the winter and
11 summer periods, respectively. Now, if the actual efficiency is only 0.75 of Carnot
12 efficiency, then these cycle efficiencies will be reduced by 25% from the values
13 above. The lower efficiencies occur in the summer, when the heat rejection
14 temperature is highest, but also when the solar insolation is highest. These two
15 effects compensate for each other, so that the effective output from a complete
16 system is relatively independent of the time/season of the year in which it is
17 running. For some embodiments of the ASTEC solar power system design, the
18 efficiencies may be taken as 0.24 for oil use and 0.15 for water/collector/storage
19 use.

20 [00031] A low-cost and reliable engine is that of the mass-produced Ford
21 Tempo or Ranger, at 140 cubic inches of displacement, with four cylinders, and a
22 compression ratio of about 8.5:1. The working fluid of interest is chosen from the
23 acceptable refrigerant fluids which do not, harm the ozone in the atmosphere.
24 These include R-134a, which acts much like earlier harmful Freon fluids, but has
25 a molecular structure that does not break up atmospheric ozone. This or other
26 similar fluids, e.g., R-123, may be used. With these, the upper temperature can be
27 matched to the output of the collector field, whether with oil or water, and the
28 lower temperature and pressure in the expansion process can be kept below 25
29 psia, with upper pressures in the range of 100-300 psia.

1 [00032] Detailed analyses of the fluid cycles shows that overall power
2 output, with the above efficiencies can reach values of about 25 and 16.5 kW
3 shaft power, respectively, when the engine is run at 2000 rpm in a Rankine -cycle
4 mode as a pure low temperature expander system.

5 [00033] In accordance with embodiments of the invention, the valve timing
6 of the engine is changed to give two-cycle operation. The exhaust valve is opened
7 at the bottom of the cycle and kept open on the up stroke, while the intake valve is
8 opened slightly before top dead center and held open as the piston goes over its
9 topmost position, to allow high pressure driving fluid into the chamber. Since the
10 intake pressure is high, the intake valve dwell time is small, while the exhaust
11 valving is open on most of the cycle for the exhaust stroke. This change in valve
12 timing is a minor correction achieved by replacement of the valve pushrod/lifter
13 camshaft with one of proper action. An improved valving system may include
14 rotary valves rather than pushrod-driven poppet valves, to reduce valve train drive
15 power.

16 [00034] If the engine speed is increased, for example to 3600 rpm to match
17 alternator/generator needs for 60 cycle electric power generation, then the engine
18 power output will rise accordingly. Since parasitic loads (e.g. oil pumps, valve
19 train power, etc) increase with speed, as well, the gain is not quite linear with
20 speed increase. Thus at 3600 rpm this engine would be expected to yield about 40
21 and 26 kW shaft power, for collector oil and water temperatures respectively..
22 Here, the design condition has been taken of only 15 kW electric output for a
23 single-engine water collector system. This has the virtue that it is very
24 conservative, and a considerable underestimate of system potential, thus — if this
25 is economic — all other systems will be even more so.

26 [00035] For an engine producing 15 kWe at 0.16 overall efficiency, the
27 thermal power that is needed to run the engine is 94 kWth. In the winter the daily
28 solar fluence of 4.8 kWthhrs/m² leads to a requirement of 900/ε_{col} square meters
29 of collection area to acquire enough energy to run throughout the full 24 hours

1 each day. Here ϵ_{col} is the energy collection efficiency of the solar collectors.
2 Conventional flat plate collectors may provide $\epsilon_{col} \approx 0.5$, while the ASTEC system
3 can reach $\epsilon_{col} \approx 0.75$ by use of its two tank approach to hot and cold storage. In
4 winter, during the daytime, the energy collected is three times that used by the
5 engine system; the rest is stored for night use. In the summer, the daily fluence is
6 nearly twice as high, but the engine cycle overall efficiency is lower than in
7 winter, by about 1/3. Thus, summer operation will give a potential output about
8 30 % higher than in winter. For design purposes, a very conservative collector
9 area of 1200 m^2 may be used with a collection efficiency of $\epsilon_{col} \approx 0.75$.

10 Solar Thermal Conversion Power System

11 [00036] The ASTEC solar power system has the advantage of providing a
12 low cost system that employs mass-manufactured equipment (e.g. auto engine
13 blocks converted to Rankine cycle expanders) and/or basic technologies (e.g.
14 stamped sheet steel, seam-welded panel plates, analogous to mass-manufactured
15 refrigerator back plane radiators) drawn from conventional production industries.
16 These elements are assembled as the principal components of the unique
17 configuration of the ASTEC system fluid flow, heating and cooling systems, to
18 permit solar energy conversion processes at lowest possible cost.

19 [00037] The key to economic solar power is cost, not simply engineering
20 efficiency. High efficiency systems traditionally cost a great deal more than those
21 of low efficiency. However, if a low efficiency system can be made sufficiently
22 cheaply, then its cost of power produced will be lower than that of the higher
23 efficiency, but more expensive system. The unique approach here, in the ASTEC
24 system, is to choose system components that are inherently low in cost, because
25 they are designed to operate at low temperature and relatively unstressed
26 conditions, thus eliminating any need for high technology in any of the system
27 components. The low-cost technologies of interest here all are found in the
28 heating, air conditioning and refrigeration industries, and in the automotive
29 industry, and are derived from mass manufactured sources.

1 [00038] The ASTEC system consists of two main subsystems: One is the
2 thermal energy collection and storage system (TCS), and the other is the thermal
3 energy conversion (TEC) system. The two subsystems are physically distinct, in
4 that the solar energy collected by the TCS system is stored in tanks of heated
5 working fluid, independent of the TEC system. The TEC system uses this stored
6 heated working fluid as the thermal power source to drive a heater-vaporizer for
7 its expansion fluid cycle. The TEC system working fluid and flow system are
8 coupled into the TCS system only through this heater-vaporizer. This permits the
9 two subsystems to be designed and optimized independently for use of solar
10 energy in the functions of each subsystem.

11 [00039] The basis principles of operation of the ASTEC system according
12 to embodiments of the invention may be understood in reference to Figs. 2-8.
13 Figure 2 shows the temperature panel performance for an un-cooled panel and
14 will be explained more below. Fig. 3 will be first described as representative of
15 the hardware components depicted in each of Figs. 2-8.

16 [00040] As shown in Fig. 3 there is provide one or more flat panel
17 collectors 1, a hot fluid tank 2, a heater-vaporizer/heat exchanger 3, a cold tank 4,
18 an expander 5 (e.g., engine), a condenser radiator 6, a controller, 7 and an
19 electrical generator 8. The heater-vaporizer/heat exchanger 3 serves as a heat
20 exchanger in the TCS system and as a heater-vaporizer in the TEC system. For
21 simplicity, the heater-vaporizer/heat exchanger 3 will sometimes be referred to as
22 the h/v 3 regardless of its function in either the TCS or TEC systems. Various
23 pumps, P1, P2, P3, and P4 are provided as well as valves V1, V2, V3 and V4 as
24 illustrated. For the TEC, the main pump 4 serves to pressurize the condensed
25 working fluid from the condenser-radiators 6, and return it to the heater-vaporizer
26 3. The TEC system also uses valve V4 as a throttle valve for control of the flow
27 system.

28 [00041] As illustrated in Fig. 3, there is also provided flow
29 meter/controllers C1 and C2 which measure the amount of fluid flow there

1 through and control same (through a valve mechanism) in accordance with
2 control signals input thereto. The flow meter/controllers C1 and C2 provide flow
3 output signals (not shown) as flow input signals, FLOWI, to the controller 7. A
4 flux meter 10 is also provided. The flux meter 10 is positioned away from and
5 not in contact with the panel collectors 1, and measures the intensity of sunlight
6 falling thereon and provides a flux output signal fed to the controller 7 as flux
7 input signal FLUXI. The flux meter 10 is calibrated against a dummy un-cooled
8 panel collector to provide a measure of un-cooled panel temperature as a function
9 of incident flux. The calibration curve is stored in a memory contained in the
10 controller 7. The controller 7 may then utilize the flux measurement provided by
11 signal FLUX1 to determine the temperature of an un-cooled panel collector.
12 Alternatively, a temperature sensor may be used attached to a dummy panel to
13 provide a temperature measure of the un-cooled panel. Further, both a flux meter
14 and a temperature sensor may be used, one providing back-up measurements to
15 the other.

16 [00042] There is further provided a temperature sensor 12 which measures
17 the temperature of the working fluid leaving the panel collectors 1 and provides
18 an output temperature signal which is fed to the controller 7. The temperature
19 sensor 12 may be attached to the output flow conduit of the flat panel collectors 1.
20 Further, temperature sensor 14 is provided to measure the temperature of the cold
21 tank 4, and temperature sensor 16 is provided to measure the temperature at the
22 output of the heater vaporizer heat exchanger 3. The temperature sensors 12, 14
23 and 16 provide inputs to the controller 7 and these inputs are shown collectively
24 in Figs. 3-8 as input TEMPI signals. The controller 7 receives flow input signals
25 FLOWI from the flow meter/controllers C1 and C2; the flux input signals FLUXI
26 from the flux meter 10; and the temperature signals TEMPI from the temperature
27 sensor 12, 14 and 16 and uses these signals to control the TCS and TEC
28 subsystems. The controller may be implemented by a digital processor and
29 provides control signals CV, CP and CC to the valves, pumps and flow
30 meter/controllers respectively to control same. The connection lines to the
31 pumps, valves etc are not shown for simplicity. The algorithm which is

1 implemented in the controller 7 will become apparent from the following detailed
2 explanation of embodiments of the invention.

3 [00043] A further temperature sensor may be provided to measure the
4 temperature of the hot fluid tank 2 to ensure that no overheating of the hot tank
5 takes place.

6 [00044] As seen in Fig. 3, the TCS system includes a simple solar energy
7 collector in the form of a one or more flat plate collectors 1, which heat the
8 working fluid, which is then supplied to the hot fluid tank 2 and thence to the
9 TEC system to vaporize the engine-expander working fluid, in the heater-
10 vaporizer heat exchanger 3. The engine-expander working fluid then drives the
11 expander 5 (modified engine described earlier), and is condensed in the low-cost
12 condenser 6, which may preferably take the form of low cost radiators, and
13 pumped back to the heater-vaporizer 3, and again heated by the TCS system
14 working fluid. The TCS system working fluid, being thus cooled by its use in the
15 heater-vaporizer is supplied either directly back to the solar collectors 1, or
16 indirectly thereto, through a cold fluid storage tank 4.

17 [00045] A heater-vaporizer 3 is driven by the hot TCS working fluid from
18 the hot tank 2, which flows in a counterflow fluid arrangement as compared to the
19 flow of the TEC working fluid. The exhaust temperature of the TCS working
20 fluid is only slightly (e.g. 5-10F) above the temperature of the condensed working
21 fluid of the TEC system.

22 [00046] The expander 3 preferably takes the form a Rankine cycle engine
23 expander supplied with the TEC working fluid vapor from the heat exchanger,
24 which expands the TEC working fluid to low temperature (e.g. 80-100 F) and low
25 pressure (e.g. 15-25 psia).

26 [00047] The TCS working fluid is typically water, but heat transfer oils
27 may be used, although at greater cost. The solar collectors are typically mounted
28 at a fixed co-latitude angle relative to the equator (in the northern hemisphere this

1 is towards the south-facing horizon) and are fixed in position so that they point
2 directly at the sun at solar noon-time. Preferably, the flat panel collectors 1 do not
3 rotate, although this more costly option may be employed. The TEC system
4 working fluid is typically, a refrigerant fluid (e.g. R-123), but organic
5 hydrocarbons (e.g. butane, pentane) may be used, although at greater cost.

6 [00048] A major feature of embodiments of the ASTEC system is the TCS
7 system flow configuration and flow control plan, developed so as to maximize the
8 collection of solar energy, even during times when the sun is not high enough to
9 drive the system directly.

10 [00049] To achieve high collection efficiency with a fixed, non-tracking
11 flat plate collector system requires that as much as possible of the solar energy
12 falling on the collectors be absorbed in the TCS system working fluid. In the
13 ASTEC system, this is achieved by use of a dual-tank storage system for holding
14 TCS system working fluid in varying amounts during the solar day.

15 [00050] The heater-vaporizer 3 is driven by working fluid at a temperature
16 T_{drv} which is desired for the drive system. This working fluid must always be
17 taken from the hot working fluid tank 2 of the TCS system. During dark times, or
18 in the early morning, if it is desired to drive the TEC system, it is necessary to
19 have excess hot fluid stored in the hot tank 2 of the TCS system. Then, when the
20 TEC system is running in the very early morning, for example, the output of the
21 TCS system working fluid will be at the coldest temperature of the TCS system
22 fluid cycle.

23 [00051] The basic principle of the ASTEC system is to collect solar energy
24 in the early and late times of the day (when solar flux is too low to heat the
25 working fluid to useful TEC system drive temperatures, T_{drv}) by use of cold
26 working fluid circulating from the heater-vaporizer 3 or cold tank 4, and returning
27 to the cold tank 4, and then to switch to flow from the cold tank 4 and return to
28 the hot tank 2 when the temperature capability of the collector panels exceeds the
29 TEC system working drive temperature.

1 [00052] The operating principles set forth above are best described by
2 reference to Figs. 2-8. The (measured) performance of an ASTEC system
3 collector panel operating without any cooling-working fluid is depicted in Fig. 2.
4 Being un-cooled panels, Fig. 2 shows the maximum temperature that the panel
5 can achieve as a function of time during the day. The data was taken on October
6 2002 in San Diego, California and is representative of a dry sunny day in
7 Southern California. The temperature vs time history is typical of such panels.

8 [00053] There are several points of time that are important for
9 understanding the flow cycle control of the ASTEC system as shown in Fig. 2.
10 Prior to time t_0 , the un-cooled panel temperature (as measured by previously
11 calibrated temperature correspondence with the flux measured by the flux meter
12 10) is below that the temperature of the fluid T_{ex} being exhausted from the heater
13 vaporizer 3. In this case, assuming that the TEC system is producing power, the
14 working fluid of the TCS goes from the hot tank 2 through pump 2 flow meter-
15 controller C2, heater vaporizer 3, valve V2 and into the cold tank 4 as shown by
16 the heavy dotted lines of Fig. 3. No TCS working fluid flows to the panel
17 collectors since the temperature of the panel collectors 1 is lower than the exit
18 temperature T_{ex} of the heater vaporizer 3.

19 [00054] When the panel temperature, T_0 , first reaches and exceeds the
20 temperature of fluid T_{ex} being exhausted from the heater-vaporizer 3, the TCS
21 working fluid is delivered from the direct discharge of the heater-vaporizer (h/v) 3
22 to the panel collectors 1 through valve V2. This TCS working fluid emerges from
23 the panel collectors 1 at a slightly higher temperature than its input temperature,
24 limited by the temperature capability of the panel 1 heated by sunshine, and is
25 returned to the cold tank 4. The path from the panel collectors 1 to the cold tank 4
26 is through the pump P1 and valve V1, and the complete path is shown by the
27 heavy dotted lines of Fig. 4. Also shown in Fig. 4 is a small graph adjacent valve
28 V3 indicating the flow level during the time interval t_0-t_1 .

1 [00055] Fig. 2 illustrates the time t_0 at which the un-cooled panel
2 temperature (as measured by the flux meter 10) crossed the heater vaporizer 3
3 exhaust temperature T_{ex} . During this time, the TCS working fluid flow rises
4 from zero as shown in the upper graph of Fig. 2. Also, the temperature of the
5 TCS working fluid as measured at the output of the panel collectors begins to rise
6 as shown in the line labeled "fluid temp" of Fig. 2.

7 [00056] When the solar flux incident on the panels has become sufficient to
8 heat the heater-vaporizer 3 exhaust fluid alone to a temperature above T_{cold} , the
9 temperature of the cold tank 4, the valve V3 opens to allow cold fluid from the
10 cold tank 4 to be added to the h/v 3 exhaust fluid to enter the collectors 1 as
11 shown in Fig. 5. The amount of fluid from the cold tank to be mixed with the h/v
12 exhaust fluid is controlled so as to make the total flow into the panels 1 preferably
13 at but not higher than the maximum flow which is allowed for panel operation at
14 high noon, when the solar flux input is at its maximum. This maximum allowable
15 flow is set by design considerations of the maximum pressure drop allowed in the
16 collector panels. It is generally in the range of 2-4 times the flow from the h/v
17 exhaust alone. After ramp up of the total flow as shown in the upper graph of Fig.
18 2, (and also the lower left hand graph in Fig. 5), this total flow (and the mixing
19 ratio) is held relatively constant during the time intervals t_1-t_7 as the sun rises and
20 solar flux increases into the panels except for the period around t_3 as will be
21 explained below. Thus the exit temperature of collector panel cooling fluid as
22 measured by sensor 12 will rise as the sun rises. Fig. 2 shows the TCS working
23 fluid temperature, "fluid temp" during the various times of the day and it may be
24 seen to slowly rise during the time frame t_1-t_2 .

25 [00057] When the solar flux has reached that value at which the un-cooled
26 panel would operate at the temperature, T_{drv} , required for direct operation of the
27 heater-vaporizer 3 in the TEC system, the panel cooling fluid flow *could* be
28 reduced to provide fluid directly into the hot tank with a like amount of fluid
29 taken out of the hot tank and fed to the h/v 3. However, since the flow thus
30 obtained is less than that needed for fully direct hot tank flow operation of the

1 engine system, (i.e., the flow rate is insufficient to drive the h/v3 with no net drain
2 in the hot tank 2) it is more efficient, in terms of collector efficiency, to continue
3 running the maximum flow from the cold tank 4 through the collectors 1, with
4 collector panel exit flow continuing to be returned to the cold tank 4. This cycle
5 is chosen in that it is more efficient to run cooler working fluid through the panel
6 collectors 1 than warmer working fluid and to maximize the amount of cooler
7 working fluid through the panel collectors 1. Thus, the collector exit temperature
8 of the working fluid will continue to remain below that of Tdrv during the time
9 interval t_2-t_3 . Fig. 6 shows the same flow path as shown in Fig. 5, but the graph at
10 the lower left corner of Fig. 6 indicates a constant and maximum fluid flow going
11 into the panel collectors 1. Fig. 2 also shows this constant maximum fluid flow in
12 the top graph, and it is also seen that the fluid temperature of the TCS working
13 fluid continues to rise during this time interval t_2-t_3 . This rise in TCS working
14 fluid is important since high flow rates are maintained in this time interval and
15 cool working fluid is utilized. Thus the TCS working fluid may extract thermal
16 energy from the heated solar panel in a highly efficient manner.

17 [00058] Now, as the sun continues to rise and the solar flux input increases,
18 the panel will reach a condition at which its un-cooled panel temperature, as
19 measured by flux meter 10, is considerably higher than that for system drive,
20 called Topg (operating temperature). At this time, the TCS working fluid to the
21 panel collectors 1 is reduced by partially closing off the valve mechanism within
22 the flow meter/controllers C1 as determined by the controller 7 to result in a total
23 TCS working fluid flow sufficient solely to satisfy the requirements of the engine
24 system drive. Reduction in the TCS working fluid flow results in the TCS
25 working fluid temperature exiting the panel collector 1 rising to reach the
26 temperature Tdrv as shown in Fig. 2 by the line fluid temp. During the time
27 frame t_3-t_5 , after the flow drops near the time t_3 , the total flow gradually increases
28 in a manner to maintain the fluid temperature of the TCS working fluid at Tdrv.
29 Thus, gradually, between t_3 and t_4 , working fluid from the cold tank 4 is
30 increasingly added to the exhaust working fluid of the h/v 3 in the valve V3 and
31 fed to the panel collectors 1. For a TCS working fluid of water, Tdrv would be

1 near the water boiling point. Fig. 2 depicts in the upper graph the drop in the TCS
2 working fluid flow rate at time t_3 , and this drop is also depicted in the lower left
3 graph of Fig. 7. When the temperature of the working fluid (as measure by
4 temperature detector 12) reaches T_{drv} , the working fluid is now, for the first time
5 during the day, delivered to the hot tank 2 as shown by the heavy dotted lines of
6 Fig. 7.

7 [00059] As the sun continues to rise from t_3 to t_4 , the solar flux raises
8 beyond T_{opg} to the peak un-cooled temperature point at T_{max} at time t_4 . At 1300
9 hours, the TCS working fluid flow is again at its maximum allowable value, and
10 TCS working fluid which is heated thereby to T_{drv} , beyond the time of the T_{opg}
11 point, in excess of that needed to power the engine system, is then stored in the
12 hot tank 2, thus refilling the hot tank 2 for future use.

13 [00060] When the solar flux reaches its maximum at 1300 hours (time t_4
14 which is the un-cooled T_{max} point), the flow control process is simply reversed
15 from that just described, from t_0-t_4 . Now, as the sun goes down, the panel flow
16 gradually decreases until just before the point at which the T_{org} is reached where
17 the flow is decreased to where the flow would exactly equal that required to drive
18 the engine system. As the un-cooled panel temperature approaches T_{org} , the flow
19 is again increased steeply, with fluid added from the cold tank 4 mixed with the
20 h/v 3 exhaust fluid. At this time t_5 , the working fluid temperature leaving the
21 panel collectors 1 begins to drop below T_{drv} , thus again increasing panel
22 collection efficiency. TCS working fluid exiting the panel collectors is again now
23 discharged to the cold tank 4, and the engine system now is running on the stored
24 fluid in the hot tank, at T_{drv} .

25 [00061] The remaining operation from t_5-t_8 is simply the reverse of the
26 operation during the period t_0-t_3 , and the graph shown in Fig. 2 is seen to be
27 symmetrical for the sunrise and sunset portions.

28 [00062] To reiterate some of the above points, during the morning hours,
29 by the time that the system has reached the un-cooled T_{opg} time, the hot tank 2

1 has been depleted or nearly depleted by operation during the evening, night and
2 perhaps dark morning time of day. At un-cooled time T_{org} , the hot tank 2 is
3 finally able to begin being refilled. The fluid emerging from the collector panels
4 at T_{drv} is not enough to fully supply the heater-vaporizer of the TEC system,
5 however, until such time t_3 as the (un-cooled) panel temperature capability has
6 reached the temperature T_{opg} on the graph of Fig. 2. At this time the solar flux is
7 sufficient to supply all of the heater-vaporizer thermal power needs of the TEC
8 system. Keeping the panels colder than T_{drv} until this time (time $t_0 - t_3$), by use of
9 excess cooling fluid flow, renders them more efficient as solar energy collectors.

10 [00063] In the above discussion, it is reiterated that the actual temperature
11 of the TCS working fluid exiting from the panel collectors 1 will not be T_{opg}
12 shown on the Fig. 2, but will remain at T_{drv} , throughout the time $t_3 - t_5$. During
13 the times $t_2 - t_3$ and $t_5 - t_6$, while the solar power flux is insufficient to drive the
14 heater-vaporizer fully, the temperature is held below T_{drv} by control of the flow
15 of the TCS system working fluid, by its pumps and valves. These operations are
16 done to gain efficiencies in extracting heat from the panel collectors 1.

17 [00064] Again, in reference to Fig. 2, once the un-cooled panel
18 performance raises to reach the time shown for T_{opg} , its un-cooled temperature
19 plot will still rise above T_{opg} . This means that the solar flux incident on the
20 panel collectors 1 and able to be collected by the working fluid, exceeds that
21 needed by the heater-vaporizer 3, as previously described (above). During this
22 time period, $t_3 - t_5$, the flow is adjusted (increased) so as to maintain the working
23 fluid at the T_{drv} temperatures, and all of the flow from the panel collectors 1 is
24 fed into the hot tank 2. As already noted, the total flow rate during this time will
25 be greater than that required by the heater-vaporizer 3.

26 [00065] By this means of use of dual tanks, appropriate sequencing of
27 valving, and controlled variation of flow of the working fluid in the TCS system,
28 it is possible to achieve much higher solar flux collection efficiency than with
29 conventional, fixed, solar flat plate collectors which do not employ this flow

1 valving, sequencing and control. Typically, collection efficiencies in the range of
2 65-75% efficiency may be obtained by these means.

3 Solar Collector System Size, Design, Storage and Deployment

4 [00066] The plate collectors 1 are preferably designed for minimum cost
5 manufacture, using mass-produced flat plate cooler panels originally designed and
6 employed on refrigerators for coolant heat rejection to air. As a non-limiting
7 example, these collectors 1 may be made in a size of approximately 2 x 4 feet, and
8 thus fit as a module in a flat panel of 4 x 8 feet dimension. In a preferred
9 embodiment as shown in Fig. 9, four plate panels are mounted side-by-side cross-
10 wise on a 4 x 8 plywood sheet, on a layer of fiberglass insulation with foil
11 backing facing the flat panel back surface. The set of four panels may be
12 connected into a parallel flow system with merged inlet and output lines entering
13 and leaving at one side of the plywood base as shown in Figs. 9-12.

14 [00067] The plates are covered with one layer of 1/16 inch think glass, in
15 sets of 2 x 4 ft sections, which are then covered with a second glass plate array,
16 separated by a screen of chicken wire to produce air insulation space as shown in
17 the cross-sections of Figs. 13-14. The entire system is simply laid on the plywood
18 base, within its 2"x4" wood side frame pieces, glued and nailed to the base
19 plywood. The side 2x4's frame the entire collector panel.

20 [00068] The panels are mounted with the long side horizontal and the short
21 side tilted at an angle to maximize solar collection. Each such full panel is
22 fastened to a supporting 2 inch o.d. pipe frame, (or other lesser cost metal
23 structural support) set in concrete and held to the pipe by 4 mild steel bolts, for
24 easy field assembly. Each panel offers about 3.0 square meters of effective
25 collector area, thus about 168 such panels are needed to give the total required
26 collector area above. These can be arranged into 6 groups of 28 panels each,
27 placed in a rectangular array around a building (shed) containing the engine,
28 generator, controls, and thermal storage system and its heater and cooler heat
29 exchangers. The panels are spaced normal to the solar noon line, so as to avoid

1 losses due to panel/panel shadowing. This sort of modular solar power system
2 could be replicated at large scale for higher total power output.

3 [00069] Alternative embodiments of the panel construction is shown in
4 Figs. 15 and 16. The L shaped frame structure of Fig. 16 supports 5 panels
5 fabricated as shown in Fig. 15. In this embodiment, the solar panel plate may
6 have the same or similar construction as that shown in Figs. 10-13.

7 [00070] The storage system for both the hot tank 2 and cold tank 4 consist
8 of simple insulated tanks. In one embodiment, the hot tank 2 may consist of a
9 concrete-lined underground tank with a concrete roof and removable access port
10 of reasonable dimension (e.g. 4x6 ft). This is cast into a hole excavated in a power
11 conversion building area, and contains sufficient water (or oil) storage to provide
12 power during the night hours with a temperature drop of less than 25 degrees F.
13 The tank size may for example be a cube about 16 feet on a side.

14 [00071] In embodiments of the h/v 3, one may utilize a low-cost auto
15 radiator, which is capable of transferring about 100 kWth in this fluid/fluid mode.
16 The radiator may be mounted on a frame submerged in the upper portion of the
17 storage fluid, and fluid is pumped through it by means of a submersible pump
18 driving into a plenum chamber fastened to the radiator external frames.
19 Alternatively, the radiator may be separate from the hot tank and in fluid
20 communication therewith. Engine cycle fluid is pumped through the radiator, and
21 heated by the storage fluid. The cycle cooler system is based on three auto
22 radiators, each rejecting about 30 kWth to air. This is mounted above the tank in
23 the power building, and cools the cycle fluid by forced convection to the ambient
24 air (just as in automotive use). Electric power generated is fed to local
25 transmission lines for delivery to the grid or to combine with other Auto Solar
26 modules for higher grid power delivery.

27 [00072] Such a modular, simple set of components can be deployed by
28 post-hole digging for the pipe frame supports, pumped concrete from cement
29 trucks, on-site installation of the solar panel systems at the 4 x 8 ft size, and local

1 hookup of inflow and outflow lines for the collector system to the storage tank.
2 All main lines may be placed underground, with simple trenching burial, and can
3 be made from high pressure PVC or other low-cost, temperature capable plastic
4 pipe. Low-cost plastic valves can be used to isolate each panel from the common
5 supply, for maintenance and replacement, and all pumping and main valves be
6 kept in the power conversion building area. This building is a simple
7 prefabricated steel shed building, to provide weather protection for the equipment.
8 It is mounted on a concrete slab, poured as part of the floor for the underground
9 storage tank. By these means, the costs of field installation can be kept to minimal
10 levels.

11 [00073] System maintenance consists of four main items: (1) Thermal
12 conversion system fluid condition and engine cycle operation; (2) Heater and
13 cooler heat exchanger status and condition; (3) Collector/storage fluid condition
14 and fill, and; (4) Solar collector system equipment and functioning status.

15 [00074] Since the system is composed of nearly failure-proof components
16 and subsystems, and is operated at temperatures and pressures that ensure very
17 long life, the maintenance level required is absolutely minimal. Engine cycle
18 operation and thermal cycle fluid checking can be done in a matter of minutes, by
19 simple observation and gage checking on the fluid lines. If leaks are occurring,
20 these can be readily found, refills made, and seals replaced or otherwise fixed as
21 required. Maintenance of the heat exchangers is determined by visual observation
22 and inspection of their condition, and by temperature measurement using built in
23 thermocouples on their inlet and outlet lines. If malfunctions are found, the
24 exchangers may be replaced with new auto radiators, which is a simple operation.
25 Collector/storage system fluid checking consists mainly of checking for piping
26 leaks and testing for water chemistry adjustment, much like that required for
27 swimming pools, but only at an interval of about one month for each 15 kWe
28 module system. Makeup water can be added at this time, to adjust the fill level in
29 the storage pool, as may be required. Finally, the simplicity of the collector panels

1 argues for their low failure rate, and visual checking of cover plates, etc, should
2 not be required more than twice each year.

3 [00075] Similarly, the inherent simplicity of each subsystem element of the
4 system is such that fabrication and assembly of these sub-elements can be done
5 very easily, quickly and cheaply. For a large scale installation, the engines will all
6 be modified in a central shop, which will change the valve camshaft, and install a
7 reconfigured head block. This is estimated to require no more than about 2 hours
8 per engine. The collector panels are even easier, as they are assembled with fixed
9 deliverable components, from scratch, using jigs and minimal hand labor.
10 Collector flat panels are taped together, and laid into the side framed 4'x8' sheet
11 plywood base, on a thin bed of fiberglass insulation. Each of the glass cover plates
12 is then laid on to the flat panels, with the second sheet held off the first by a 4'x8'
13 piece of cut chicken wire. The entire collector panel/glass "sandwich" is then held
14 in place by weather strips fastened to the frame interior. Completed panels are
15 then shipped to storage or the field. The wood frame pieces are all precut, drilled
16 and slotted in a factory setup, before delivery to assembly.

17 [00076] The other subsystem elements, heat exchangers, pumps,
18 generators, switchgear, valving, etc, are all quantity manufactured items and are
19 shipped to assembly storage or to the field site for system assembly. Everything
20 needed for field installation is prefabricated and delivered to the site in condition
21 for immediate installation and use. Field operations then consist solely of
22 equipment mounting, base construction (concrete tank, post supports, floors, and
23 prefab building setup) collector panel, engine, generator and associated piping and
24 wiring installation, and fluid line filling. Upon completion, the electrical output
25 lines must be connected to the local grid and the system started up and set to run
26 at minimal starting speed and/or power. This will require about 3-4 days of solar
27 heating of the fluid system to establish the storage tank thermal capacity. After
28 this time, the system can be set to run at any desired engine speed or electrical
29 output, within its overall capabilities.

1 [00077] It is estimated that the unit plant module of the ASTEC solar
2 power system, may be built for a specific power investment cost less than
3 \$1000/kWe at the 15 kWe level which is attained with only 200 degrees F
4 maximum temperature from the solar collector arrays. This is to be compared
5 with the specific power cost of conventional oil, coal and gas-fired plants, which
6 lie in the range of 1000-1500 \$/kWe. And, of course, these plants have additional
7 fuel costs during operation, while the ASTEC system plant does not. And, it is
8 important to note that an easy upgrade to 300 degrees F is possible by use of
9 thermal oils instead of water in the collector system. This would raise the power
10 output to about 25 kWe, and reduce all specific costs to about 60% of the values
11 given above.

12 [00078] While embodiments of the invention have been described, it will
13 be apparent to those of skill in the art that various modifications and substitutions
14 may be made thereto and the invention is intended to cover all such modifications
15 and substitutions that fall within the scope of the appended claims as may be
16 understood from the forgoing written description.